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Design and Analysis on Interference Fit in the Hardwood Dowel-glued Joint by Finite Element Method

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Abstract

The wood dowel is often used in connection of furniture members due to its convenience. However, it is common to see the wood dowel unfastened in the furniture joint. In order to reinforce traditional dowel-glued joint, a research was undertaken to investigate the feasibility of design and analysis of interference fit in the dowel-glued joint by the finite element method (FEM). Since the joint consisted of the dowel and board member, many factors might influence strength of the joint. The ring angle and board type, two of most concerned factors, would be the examined in this study. On the based of this research it was found that design and analysis of interference fit in the dowel-glued joint by FEM was allowed and the withdrawal strength of wood dowel was significantly influenced by the ring angle and board type. These results would benefit performance evaluation and development of dowel-glued joint design and serve as a reference for practitioners.

Selection and peer-review under responsibility of the National Tsing Hua University, Department of Power Mechanical Engineering

Keywords: Finite element method; furniture; interference fit; ring angle; wood dowel-glued joint.

Nomenclature

FEM	finite element method
E	elastic modulus
G	shear modulus

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Greek symbols	
θ	ring angle
μ	poisson's ratio
α	swelling coefficient
Subscripts	
l	longitudinal direction
r	radial direction
t	tangential direction

1. Introduction

Furniture is an apparatus needed in human daily life. The design and construction of furniture is an applied art. The requirements for furniture design are not only appealing appearance and current fashion but also sound functionality and structural safety. The most concerned requirement is the structural safety of furniture. The structural safety of furniture includes strength of member itself and joint. In general, the wood furniture under loading almost fails in the joint, not member itself. Therefore, the design of joint strength is no less important than the design of member strength.

Almost classic and elegant furniture is made of solid wood. Wood dowel is often used in connection of furniture members due to its convenience. However, it is common to see the wood dowel unfastened in the furniture joint because wood is hygroscopic. The moisture content of wood varies with change of air relative humidity, which causes the shrinkage and swelling of the joint consisted of wood dowel and board member with holes. Consequently, the joint strength will be affected by this change. If the issue is ignored, looseness of connection is commonly seen in the solid wood furniture. An improved design idea came with design of interference fit widely used for connecting two metal cylindrical parts. The interference fit means that assembling two parts by pressing or shrinking one member onto another creates a contact pressure and friction force at the interface of two mating parts. With proper design of interference fit in the dowel and board member with holes, the connection might be tied firmly.

In recent surveyed studies on interference fits by the finite element method (FEM), one of the earliest papers found was published by White and Humpherson [1]. They used FEM to analyze the stress in shafts due to interference-fit hubs. Ohte [2] determined the surface contact stresses between any two elastic bodies with friction at the contact surface. Okamoto and Nakazawa [3] proposed a simplified algorithm based on finite incremental contact analysis with various frictional conditions. Prasad et al. [4] found their results by FEM were in good agreement with results by Lame's equation at the center point of the fit. Zang et al. [5] found that the Lame's equation could not well estimates for the interference stresses and deformation of complex geometry. Furthermore, they presented 3-D FEM that could give more complete and accurate results. Ozel et al. [6] analyzed stresses of shrink-fitted joints for various fit forms via FEM. They found that the appropriate fit type was to be stepped or not for shaft and the geometries of hub whose edges were wasted. Gamer U. and Lance RH [7] analyzed the residual stress in a shrink fit. The stresses and deformations in the thin rings and disc after being interference-fitted thermally or not were analyzed. The fit-length of which plastic deformation occurred was determined [8, 9].

The purposes of this study were two folds. First of all, showing interference stresses due to hygroscopic strains via the FEM was allowed. Secondly, presenting the effects of the board type and ring angle of wood dowel on the strength of the joint was significant. The definition of ring angle (θ) shown in Fig. 1 was the angle between the dowel grain direction and the board grain direction.

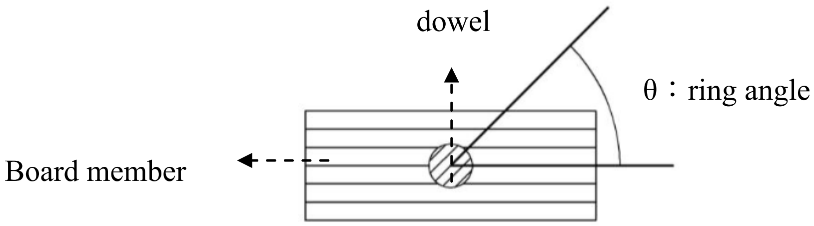

Fig. 1. Ring angle of dowel.

2. Materials and Methods

In order to take advantage of the geometric symmetry of the model, the quarter symmetric model was taken to simulate this contact problem. The finite element model was built as follows. The dowel and board member with a hole were modeled, meshed by Ansys Solid185 element and shown as Fig. 2. The width, length and thickness of board member with a hole were 0.06, 0.06 and 0.02 m, respectively. The diameter and length of wood dowel were 0.02 and 0.065 m, respectively. The diameter of a hole was 0.01 m. The contact between the dowel and board member with a hole were modeled using a contact pair of elements,Targe170 and Conta174, respectively. Two load steps were used to set up the analysis. Load step 1 (interference fit) was set to solve the problem with no additional displacement constraints to observe the interference stresses caused by hygroscopic strains between the pin and pinhole. Load step 2 was set up through moving the pin by 0.01 m out of board member with a hole and using degree of freedom (DOF) displacement conditions on coupled nodes. Explicitly automatic time stepping was invoked to guarantee solution convergence. The results were read every 10^{th} sub-step during solving. The boundary condition was applied by setting the left side surface of board member with hole to be fixed. The swelling load was applied by change of moisture content of samples from 10% to 18%. The interference fit between the dowel and board member with hole was modeled by structural static analysis with the effects of hygroscopic strains included.

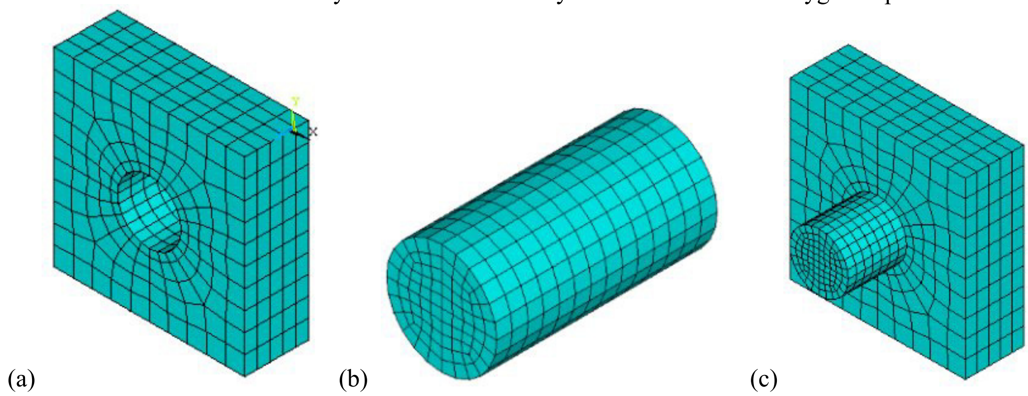

Fig. 2. Meshed models: (a) board member with a hole; (b) wood dowel; (c) Joint.

Sugar maple was used in this study and its material properties were listed in Table 1 [10].

Table 1. Mechanical properties of Sugar maple.

Material	E_l GPa	E_r GPa	E_t GPa	G_{lr} GPa	G_{lt} GPa	G_{rt} GPa	μ_{lr}	μ_{rt}	μ_{tl}	μ_{rl}	μ_{tr}	μ_{lr}	α_l	α_r	α_t
Sugar maple	1.38	1.31	0.68	1.01	0.753	0.255	0.5	0.82	0.025	0.044	0.42	0.46	0.00015	0.0021	0.0033

Two levels of board type (quarter-sawn, flat-sawn) and four levels of the ring angle (0^o, 30^o, 60^o, 90^o) on the dowel withdrawal strength were investigated. The moisture content of sugar maple changed from 10% to 18%.

3. Results and Discussion

3.1. Shape change of specimen before and after swelling.

The shape change of board types and dowels with two ring angles before and after swelling were simulated by Ansys finite element software. They were shown in Fig. 3 and 4, respectively. The dash-line shape represented shape before swelling. In aspect of the shape change, it was not surprising that the original circle before swelling became oval after swelling. It was as expected that the deformation in the tangential direction was more than that in the radial and longitudinal direction since the tangential swelling coefficient is the biggest.

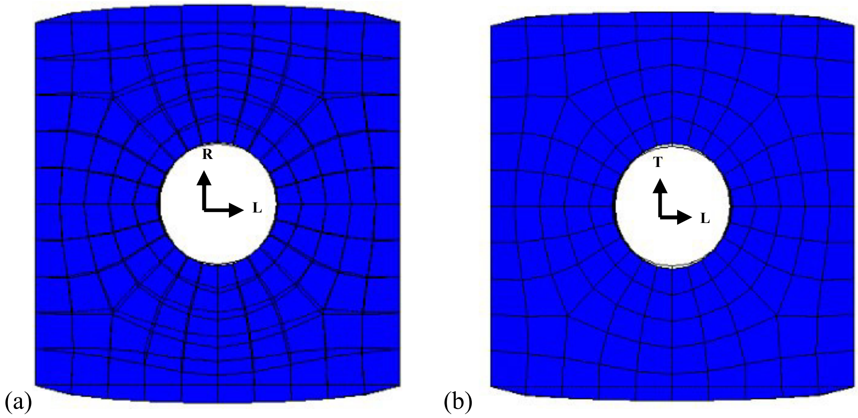

Fig. 3. Shape change of board type before and after swelling: (a) quarter-sawn board; (b) flat-sawn board.

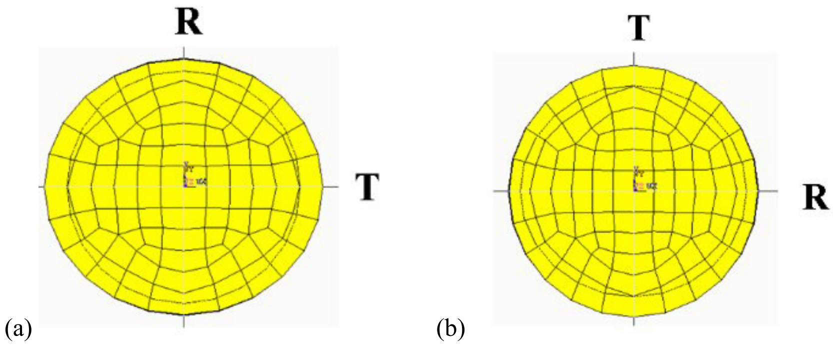

Fig. 4. Shape change of wood dowel before and after swelling: (a) 0^o annual ring; (b) 90^o annual ring.

3.2. Observation of interference fit stress state.

The stresses of wood joint after swelling were determined by FEM. These stresses could be read by the color bar and were shown in Fig. 5. The red indicated high stress area. It was interested to note that the von Mises stress distributed along the dowel hole was not even due to orthotropic wood.

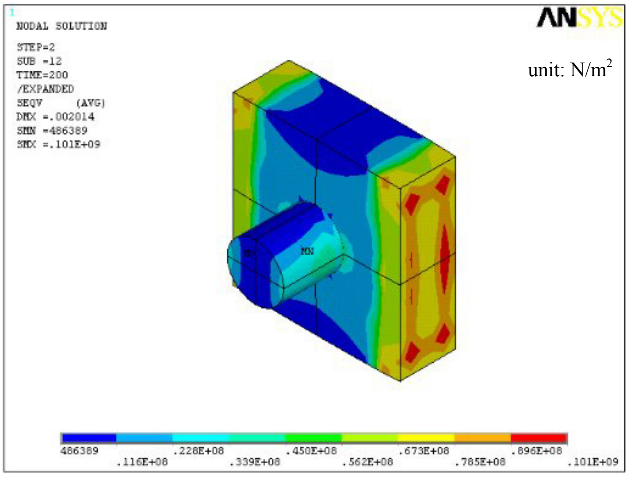

Fig. 5. Interference Stress state of dowel joint.

3.3. Observation of contact pressure on dowel.

The normal stress distribution of wood dowel subjected to load from swelling board member with a hole was main concern and plotted in Fig. 6. These von Mises stresses could be read by the color bar. Entirely, it showed that the von Mises stress decreased from tangential to radial direction and the von Mises stress in the middle of contact was higher than that in the ends of contact. The orthotropy of wood could be explained by the change of tangential to radial direction.

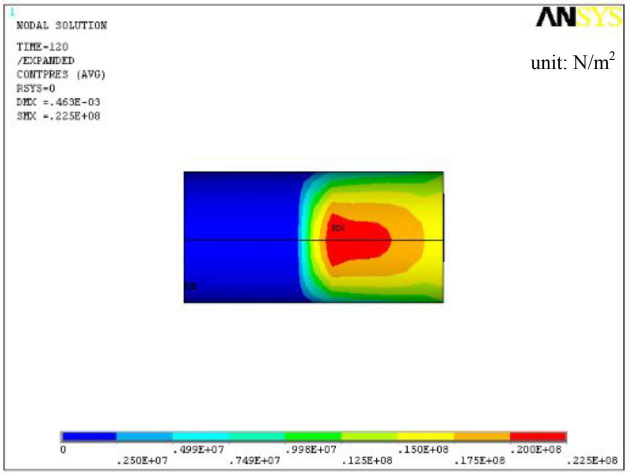

Fig. 6. Distribution of dowel normal stress from member with hole after hygroscopic swelling.

3.4. Observation of reaction force for dowel withdrawal from a board member

In order to observe the effects of dowel withdrawal from the board member, a displacement, 0.01 m, was applied to all nodes on the front of wood dowel. The reaction force for dowel withdrawal from the board member was plotted by picking a node on the front surface. It was shown in Fig. 7. The reaction force increased until the maximum. After the maximum the dowel gradually pull out from the board member. The reaction force for dowel withdrawal was picked by the maximum value.

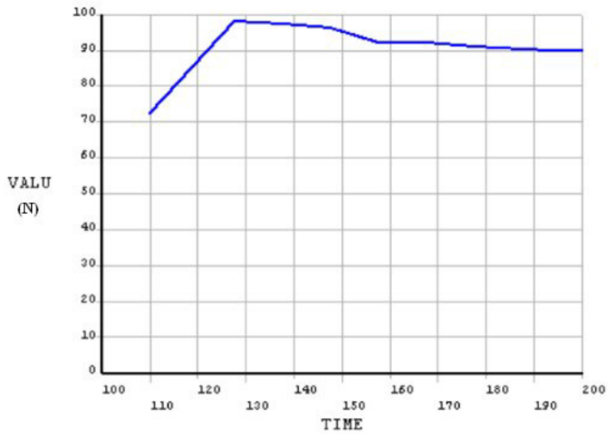

Fig. 7. Reaction force for dowel withdrawal from a board member.

3.5. Effects of the board type and ring angle of wood dowel on the dowel withdrawal strength.

In order to investigate the influence of the board type and ring angle of wood dowel on the dowel withdrawal strength, two levels of board type (quarter-sawn, flat-sawn) and four levels of the ring angle (0^o, 30^o, 60^o, 90^o) were used. The results were listed in Table 2. Table 2 presented that the dowel withdrawal strength in the quarter-sawn type board was more than that in the flat-sawn type board. The dowel withdrawal strength increased with increase of the ring angle. In terms of the overall performance of dowel withdrawal strength, it was evident that the best design of joint was found using quarter-sawn type board and ring angle 90^o.

Table 2. Effects of the board type and ring angle of wood dowel on the strength of the joint.

		Ring Angle			
		0	30	60	90
Board Type	Quarter-sawn	67.3 N	75.8 N	90 N	98.2 N
	Flat-sawn	61.6 N	69.8 N	83.6 N	91.1 N

4. Conclusions

On the base of this study, the following conclusions could be drawn: The analysis and design of interference fit for wood dowel joint by FEM was allowed; The withdrawal strength of wood dowel was influenced by these two factors (board type, ring angle) and the best design of joint to obtain highest withdrawal strength of dowel was found using quarter-sawn type board and 90^o ring angle. The fruitful and reliable results will benefit performance evaluation and development of wood dowel joint design and serve as a reference for practitioners.

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